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Hybrid Laminar Fin Investigations

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ABSTRACT

In order to evaluate the HLFC concept which is seen as the most promising drag reduction technology for transport aircraft applications Airbus Industrie launched some years ago the laminar fin programme. The paper briefly describes the main phases of this programme, i.e. the theoretical evaluation, the experimental verification through adequate wind tunnel tests and the flight test demonstration with the Airbus A320 n° 1 as testbed.

It will be shown that the initial phase conducted by ONERA allowed the A320 fin to be chosen as the support for further HLF investigations. The next phase was devoted to wind tunnel tests of a ½ scale model in the S1MA wind tunnel. Carried out by ONERA and DLR, these tests enabled the flight test demonstration to be launched by Airbus Industrie and the partners. The flight tests have then been performed by the Airbus partners under the leadership of Daimler Chrysler Aerospace Airbus in the frame of the 3E/LATEC programme. Important topics like surface and suction imperfections have also been addressed during the flight tests as part of the EC-programme HYLDA. The main outcome at that stage of the analyses is an unambiguous proof of concept.

I – INTRODUCTION

The most efficient way to reduce skin friction drag is undoubtedly to maintain laminar boundary layer as far as possible by delaying the transition process. With the given Reynolds numbers and sweep angles on modern transport aircraft only the Hybrid Laminar Flow Control (HLFC) concept seems to offer, at least from aerodynamic point of view, a solution which presents the highest drag reduction potential with remarkable fuel burn savings of up to 15%. This concept basically combines suction in the leading edge region with favourable pressure gradients after the front spar of the wing or other aircraft components like horizontal tail, fin and nacelle.

The previous statements which are generally accepted are possible thanks to significant progress in transition research [1]. However, the availability of reliable transition prediction tools does not mean that the technology which does not only involve aerodynamics, but also systems, structures, etc., is ready for application. Nevertheless, Airbus Industrie soon demonstrated its interest in the development of this demanding technology [2] and defined a long term strategy plan which implied as first step the Laminar Fin Programme [3, 4].

The choice of the fin was essentially dictated by pratical considerations in view of a flight test demonstration. Without de-icing and high lift systems it offers significant advantages for the integration of the suction system in the leading edge. However, the high leading edge sweep constitutes an additional challenge from an aerodynamic point of view.

The purpose of the paper is to give an overview of the main phases of the Laminar Fin Programme, i.e. the theoretical evaluation, the experimental verification and the flight test demonstration.

II – THEORETICAL EVALUATION

The first phase of this programme was devoted to the theoretical evaluation of the laminarisation potential for the selected Airbus A320 fin. Carried out by ONERA this study led to rather encouraging results which may be summarized as follows :

- Due to its high leading edge sweep angle and cruise Reynolds number all relevant transition mechanisms may occur on the fin, i.e. Attachment Line Transition (ALT), transition due to Cross Flow Instabilities (CFI) in the leading edge region and transition due to Tollmien-Schlichting Instabilities (TSI) further downstream.

- An ALT-avoidance device is mandatory to prevent the fin from being turbulent at the attachment line.

- Suction ahead of the front spar would stabilize the laminar boundary layer and delay transition due to CFI.

- As a result of an adequate , but not optimised fin section extended laminar flow up to 50% of the chord could then be expected, the transition occurring through TSI.

In cruise conditions the situation is described by figure 1 in terms of the required suction power, the drag reduction of the fin and the corresponding fuel burn savings. As a matter of fact, assuming a suction power of 30 kW a drag reduction as high as 38% which corresponds to fuel burn savings up to 1.3% has been predicted.

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III – EXPERIMENTAL VERIFICATION THROUGH WIND TUNNEL TESTS

At that point the experimental verification of these results appeared as the next obvious step. This was the aim of the second phase for which DLR joined ONERA and Airbus Industrie. The milestones were the design, the manufacture and the testing of a suitable wind tunnel model.

III.1 – Design aspects

In order to achieve in this wind tunnel test flight Reynolds numbers at cruise conditions a ½ scale model has been chosen to be tested in the ONERA S1MA wind tunnel. The major aerodynamic problems which had to be overcome during the design phase were the attachment line contamination and the transition by CFI through suction.

The solution for the first item consists of implementing a so-called Gaster-bump [5]. Its purpose is to create a stagnation point on the leading edge near the root which enables the disturbances coming from the fuselage to be deviated and a new laminar boundary layer to be generated. As a result of a careful design made by ONERA and based on advanced CFD-tools [3] the final shape which is schematically illustrated in figure 2 is supposed to fulfil all requirements in terms of Mach number and side slip angle range.

A critical issue for the second item and therefore a successful application of HLFC is the design of a suction system which constitutes a compromise between numerous aerodynamic and structural constraints. The layout of the final design for the A320 fin model which has been carried out by DLR is shown in figure 3. It is characterized by 45 compartments separated by stringers on which the laser drilled titanium panel manufactured by AS&T is glued. The compartments are connected in such a way that the suction mass flow can be controlled through 15 independent suction chambers and ducts. For this case figure 4 gives an impression of the theoretical pressure and velocity levels in a given section taking into account the static wall pressure and the mean suction velocity to be applied. This implies the choice of the characteristics of the perforated panel which is dictated by the following parameters :

- maximum and minimum mean suction velocity for each of the suction chambers ;

- uniformity of the local suction distributions.

It will be shown later that all these aspects were not completely mastered during this model design phase.

III.2 – S1MA wind tunnel tests

A first test campaign took place in 1993. The photo of figure 5 shows the test set-up in the ONERA S1MA wind tunnel. The 2.9 m span model which was built by Aero-construct under the responsibility of DLR is made of a glass-fibre reinforced expoxy shell connected to a steel spar by bolts. The model is equipped with an adjustable rudder. Due to its structural concept it allows the transition to be detected by infrared cameras. In order to avoid disturbances to be created its instrumentation is reduced to the strict minimum. The perforated panel of the suction nose can be clearly identified on the same photo.

Furthermore, in order to enable a HLF test to be performed in the S1MA wind tunnel an external suction device compatible with total force measurements by means of a half model wall balance has been developed. As depicted by the scheme of figure 6 the corresponding setting up including control and metering devices for up to 18 suction ducts is installed under the floor of the test section, the driving unit being an ejector.

The test campaign was a success, even if all the expected results were not observed. In particular, it demonstrated the effectiveness of the Gaster-bump in preventing ALT in the whole Mach number and the side slip angle range. As an example figure 7, exhibits RMS values delivered by a hot film which is located downstream of the Gaster-bump as a function of Mach number. The values correspond always to laminar flow which only becomes turbulent when a trip wire is placed on the bump as shown by the sketch of the same figure.

The achieved suction rates enabled laminar flow to be fully demonstrated up to a Mach number of 0.6. For higher Mach numbers a reduced laminar flow extent was observed in the root region of the fin model. This is clearly shown by figure 8 which reproduces infrared images of the fin model for different Mach numbers. As part of a detailed analysis of these experimental results compressible stability computations have been performed and the e^N method has been used following the envelope strategy to estimate the theoretical transition locations.

The input to these computations was first of all a streamwise velocity distribution deduced from the pressure measurements using a conical flow assumption. Then local suction velocity distributions derived from DLR measurements by means of a miniaturized probe constituted the necessary boundary conditions for 3D laminar boundary computations.

The sections in which pressure distributions and local suction velocity distributions have been measured are specified in figure 9. Two examples of such local suction velocity distributions are shown in figure 10. They correspond to data points at M = 0.6 and 0.78 in section 1 near the root. One has to notice the strong variation of the local suction velocity along the chord. In addition, the values obtained at the leading edge are rather small. The results of the corresponding stability computations are illustrated in figure 11. At M = 0.6 the experimental transition location at 50% of the chord corresponds to a N-factor of 10, a value which seems very acceptable. Furthermore, the N-factor does not exceed a value of 3.5 on the suction panel itself in this case. On the other hand, at M = 0.78 transition experimentally occurs on the suction panel itself. In that case, the N-factor reaches values as high as 8 in this area.

This means that the computational analysis was consistent with the experimental results. It showed that the local suction rates near the root were insufficient and smaller than the nominal values due to same deficiencies of the actual model suction system especially on the leading edge at the root of the model.

In this situation, the interest to continue the wind tunnel investigations was recognized. As a consequence, after rework of the suction nose by DLR a second test campaign was prepared and performed in 1994. Due to an increased porosity of the suction panel higher suction rates were achieved. The results clearly showed an improved situation in the whole Mach number range, but even in these tests it was not possible to demonstrate at cruise conditions the full amount of laminar flow predicted [6]. At the time being a new suction nose is under preparation at DLR and subsequently a new test campaign.

IV – FLIGHT TEST DEMONSTRATION

Nevertheless, on the basis of the first wind tunnel results Airbus Industrie and partners already decided in 1993 the go-ahead for the flight test preparation of the A320 HLF fin.

In the framework of the Airbus 3E/LATEC programme this project was shared by Aerospatiale Matra Airbus, BAE Systems, CASA and Daimler Chrysler Aerospace Airbus as the responsible partner, in association with ONERA and DLR. The multidisciplinary work which involved, apart from aerodynamics, systems as well as structures and materials was seen as an exciting challenge [7] for the Airbus world in many aspects.

Of course, special attention has been paid to the design of the on-board suction system and the suction nose. In particular, a better knowledge of the suction panel characteristics was necessary [8]. The figure 12 schematically illustrates the main features of this suction nose which is constituted by 9 independent suction chambers covered by 2 perforated panels NT1 and NT2 with a total length of 5 m. Furthermore, the leading edge is equipped in the root region of the flight test article with a Gaster-bump as ALT-avoidance device. Its design is the same as in the previous S1MA wind tunnel tests which have demonstrated its efficiency.

Another key-point has been the flight test instrumentation of the HLF fin. As sketched in figure 13, it includes pressure taps in 3 sections, a wake rake with transverse mechanism, 2 infrared cameras installed on the horizontal tail plane (HTP) in order to visualize the transition locations on both sides of the fin, hot films along the attachment and on one side of the fin.

IV.1 – Turbulent reference flight tests

The Turbulent reference Flight Tests (TFT) were performed with the Airbus A320 n° 1 in Toulouse in 1995. The fin was not equipped with its suction nose, but the Gaster-bump was installed on the leading edge near the fin root. Among others one aim of these tests was to check the critical issues of the flight test instrumentation, i.e. the installation of the infrared cameras and the wake rake. On the photo of figure 14 which shows the A320 during TFT 3 pressure belts and the wake rake on the fin as well as the infrared camera housing on the HTP can be easily identified. All these items have been successfully checked.

As far as the Gaster-bump is concerned these tests also confirmed its efficiency as ALT-avoidance device.

IV.2 – Hybrid laminar flow flight tests

Finally, the Hybrid Laminar flow Flight Tests (HLFT) took place still in Toulouse in 1998. The Airbus A320 n° 1 as flying test bed was now equipped with the complete HLFC system of the fin. It is shown on the photo of figure 15 during these flight tests.

The main part of these tests has been performed in the frame of the nationally founded Airbus 3E/LATEC programme. In addition, specific tests devoted to surface and suction imperfections have been carried out in the frame of the european EC founded HYLDA programme [9].

The flight test conditions covered a wide range of various parameters : Mach number, altitude and side slip angle. Different suction rates from the necessary minimum to the achievable maximum have been applied. Of course, a huge amount of data was measured and recorded for basic and further analysis which is under way by the partners and will take still a long time.

In the following some relevant examples of basic results will illustrate the main features. First of all, figure 16 exhibits the measured pressure distributions on the fin at cruise conditions which are in rather good agreement with the predictions. This is an important issue for the boundary layer and stability analysis. Then, the Gaster-bump efficiency as ALT-avoidance device is demonstrated by figure 17 which represents power spectra of the hot films located along the attachment line. All these power spectra reveal laminar flow except that derived from the hot film situated upstream of the Gaster-bump which is indeed turbulent as expected. This holds for the whole Mach number and side slip angle range. One has to bear in mind that without this device the fin boundary layer would be turbulent from the attachment line.

Due to HLFC extended laminar which flow regions occur on the fin which have been detected by the infrared cameras. The figure 18 shows transition locations for different side slip angles gives an impression of the quality achieved. Each view of the fin is composed by 3 partial images taken from the HTP. A basic analysis of these transition visualizations enables the laminar flow extent on the fin to be determined at cruise conditions for different side slip angles. The resultats are illustrated by figure 19. An insight in further analysis through stability computations can be found in [10].

From pratical point of view future product applications of HLFC will also depend on the robustness of laminar flow. During the HYLDA flights, the effect of local disturbances has been investigated. Therefore, 2D and 3D surface and suction imperfections of various dimensions have been introduced in the laminar flow of the fin. Typical examples are given by figure 20 which illustrates the effect of cylinder type roughness elements with different heights on the transition location and figure 21 which shows the corresponding effect of circular regions without suction. Of course, all these results constitute a valuable data base for the future development of the HLFC technology.

V – CONCLUSIONS

In order to evaluate the HLFC concept for transport aircraft applications in the framework of the Laminar Fin Programme defined by Airbus Industrie a complete cycle of investigations has been performed :

- the theoretical evaluation enabled the A320 fin to be chosen as the support ;
- the experimental verification through S1MA wind tunnel tests of a ½ scale HLF fin model led to the decision of Airbus Industrie and the partners to proceed with a flight test demonstration ;
- the flight tests performed with the Airbus A320 n° 1 under the responsibility of Daimler Chrysler Aerospace Airbus were a complete success. The results the analysis of which is in progress constitute a valuable data base.

With the HLF fin programme the proof of concept has been produced. Therefore, it represents an important milestone for the further development of this technology in Europe.

The ONERA-DLR co-operation proved to be fruitful and efficient in the initial phases of this programme. Both Research Establishments had also a significant contribution to the final phase.

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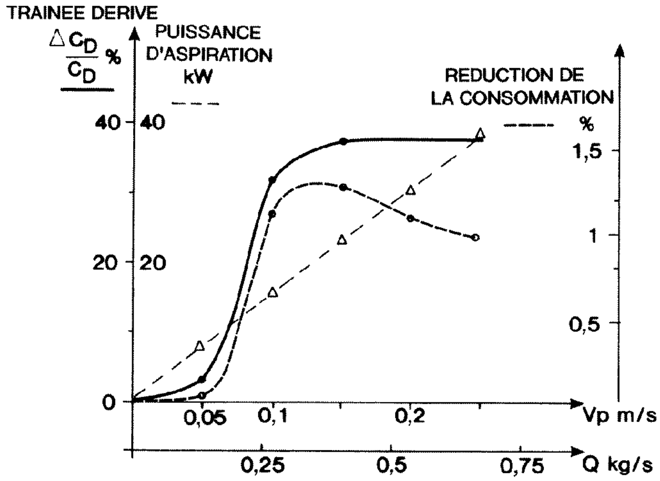

Fig. 1 - Estimated performance of the A320 laminar fin

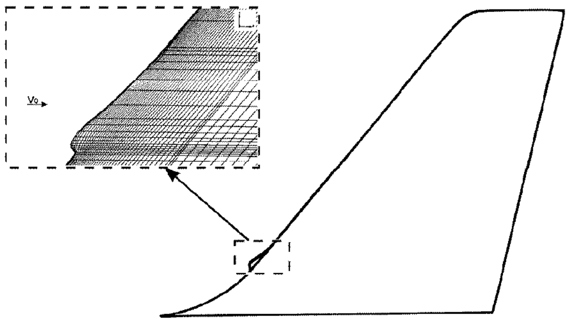

Fig. 2 – Implementation of a Gaster-bump on the leading edge

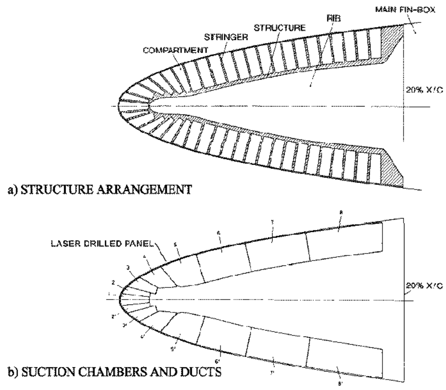

Fig. 3 - Details of the suction nose

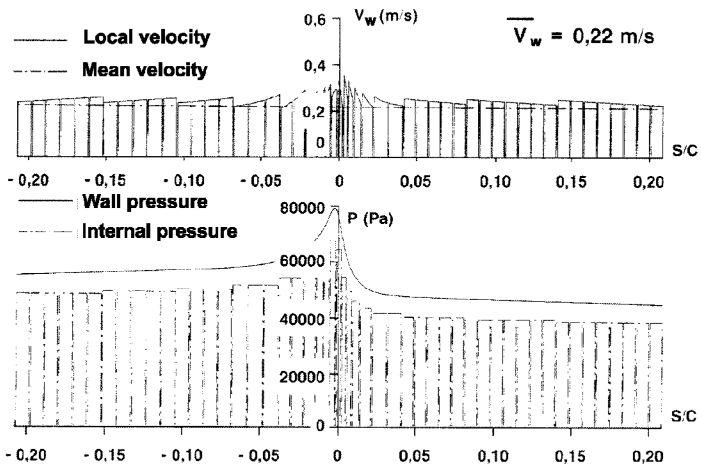

Fig. 4 - Suction velocities and pressures

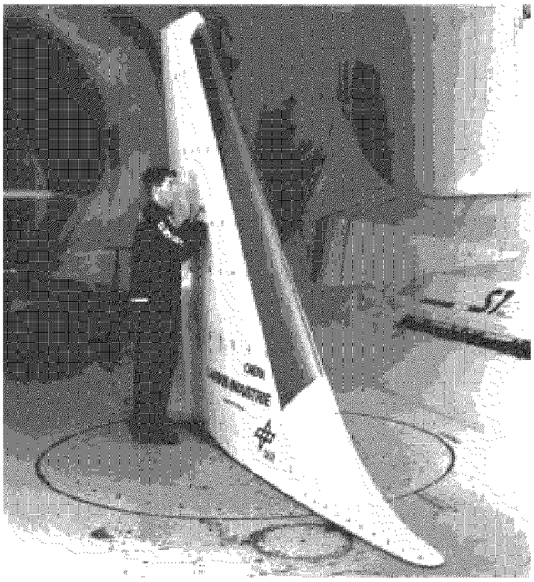

Fig. 5 – Test set-up of the A320 fin model

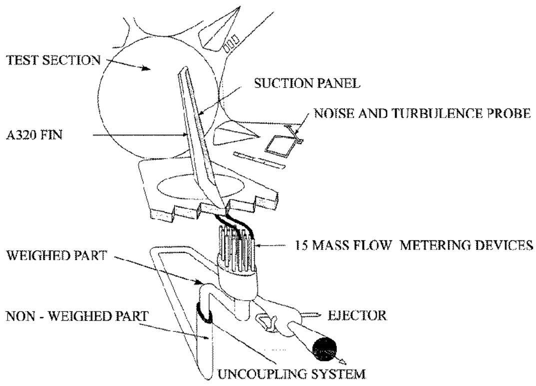

Fig. 6 – External suction device arrangement

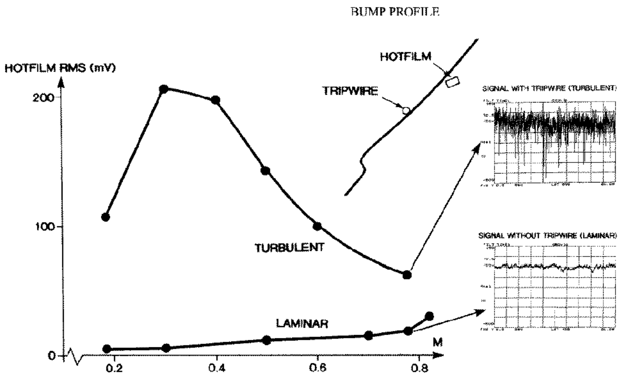

Fig. 7 – Gaster-bump efficiency as a function of the Mach number

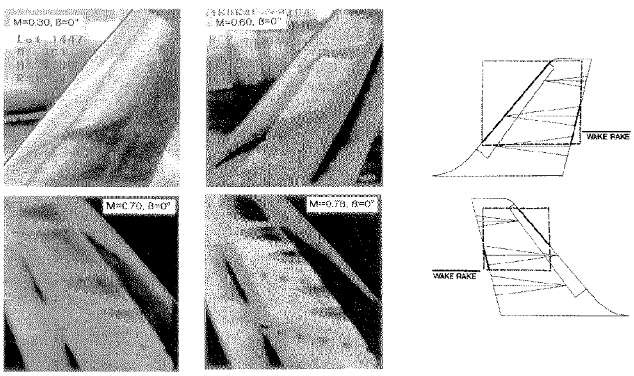

Fig. 8 – Laminar flow extent for different Mach numbers

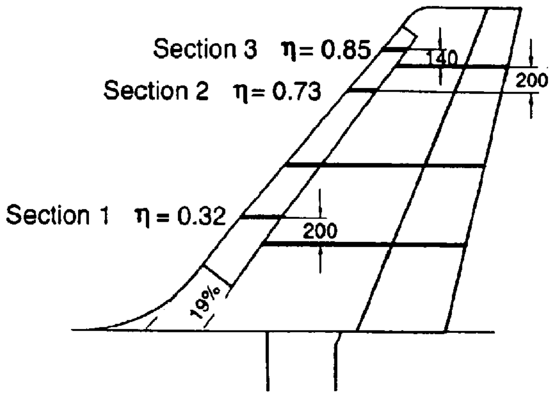

Fig. 9 – Sections with pressure and local suction velocity measurements

SECTION 1, LEFT SIDE

DATA POINT 585 DATA POINT 603

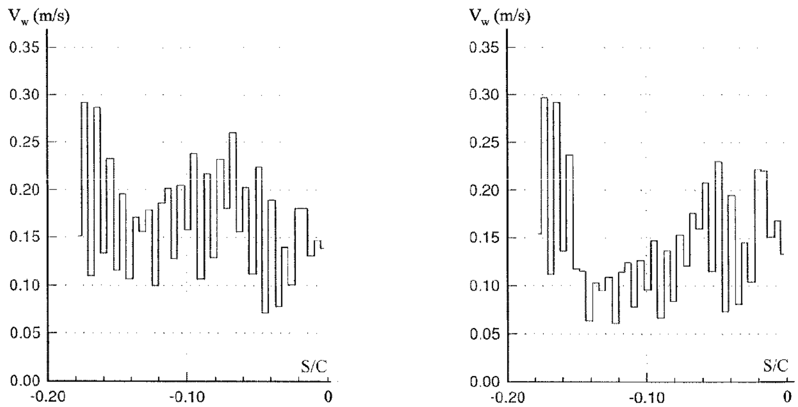

Fig. 10 – Measured suction distributions

β = 0, SECTION 1,LEFT SIDE

DATA POINT 585 DATA POINT 603

M = 0.6 M = 0.78

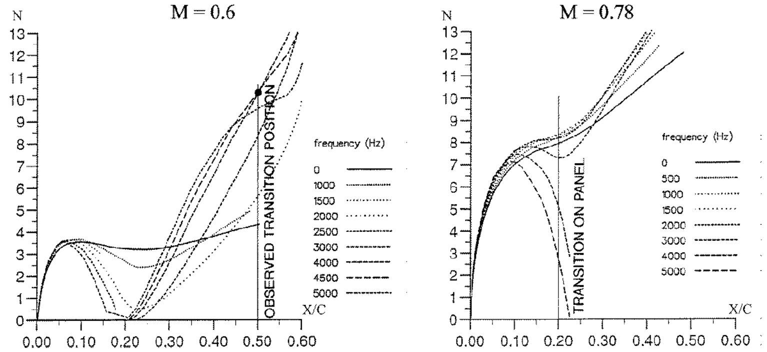

Fig. 11 – Stability analysis

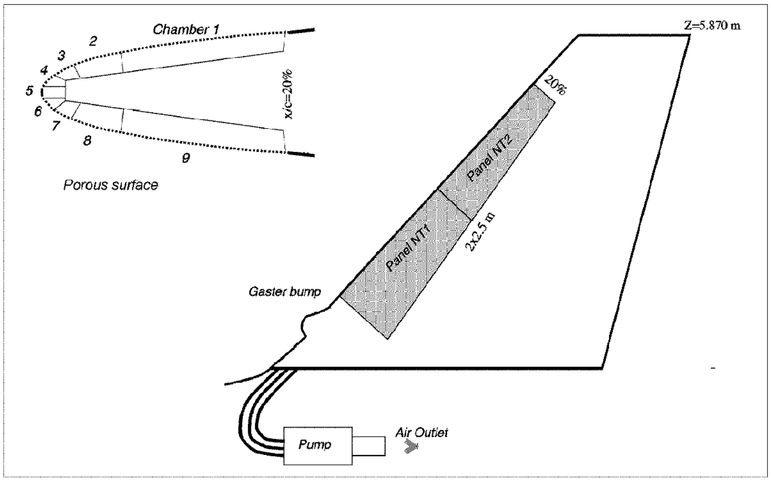

Fig.12 – Schematic suction nose layout

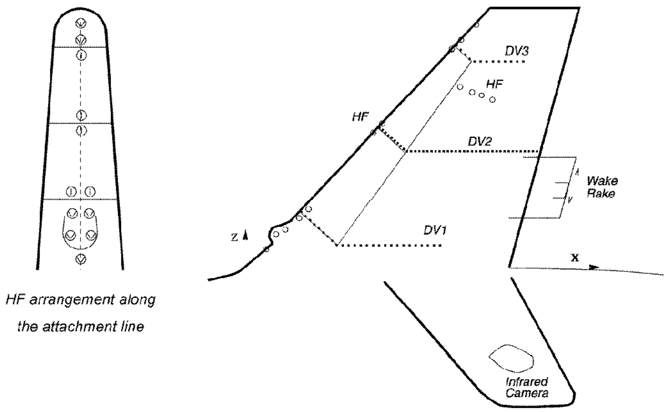

Fig. 13 – Flight test instrumentation

Fig. 14 - View of the A320 fin with flight intstrumentation

Fig. 15 – A320 HLFC fin flight tests

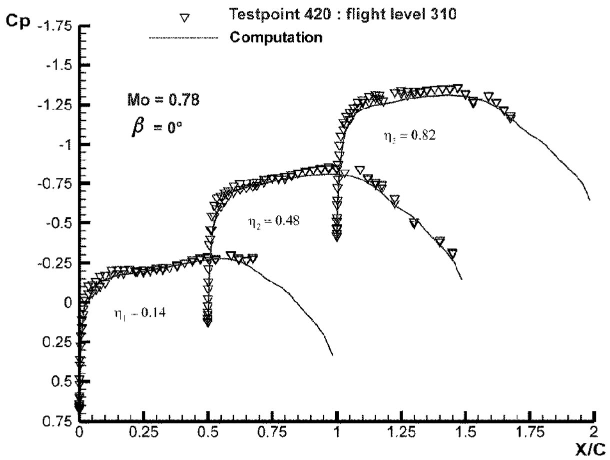

Fig. 16 – Pressure distributions at cruise

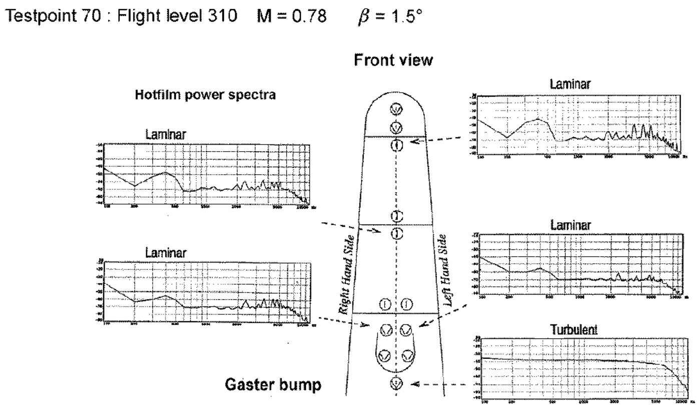

Fig. 17 – Gaster-bump efficiency at cruise

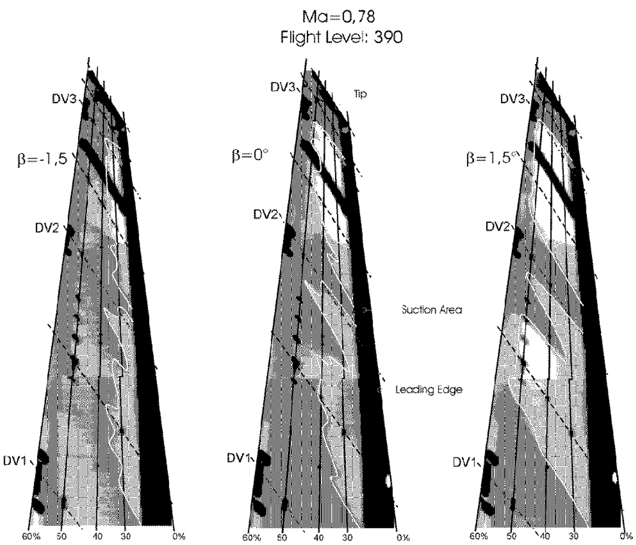

Fig. 18 – Transition locations for different side slip angles

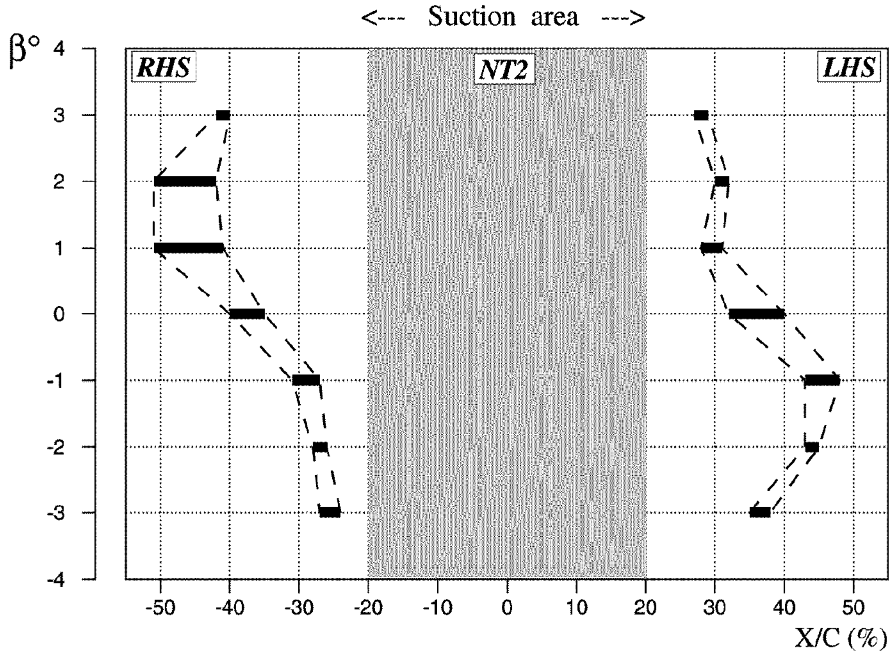

Fig. 19 – Laminar flow extent at cruise

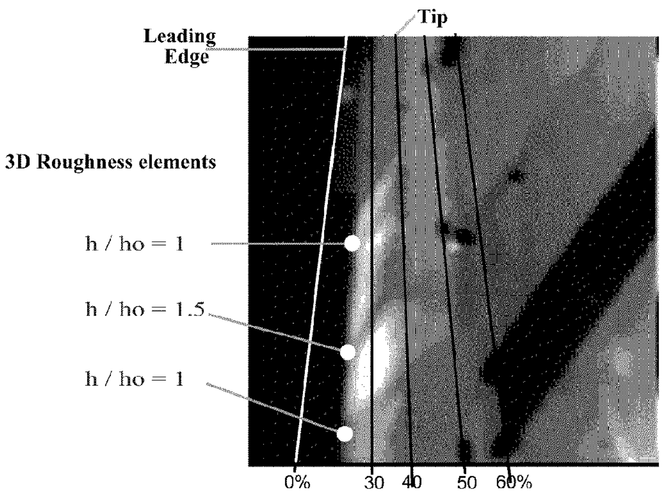

Fig. 20 – Roughness effects on transition locations

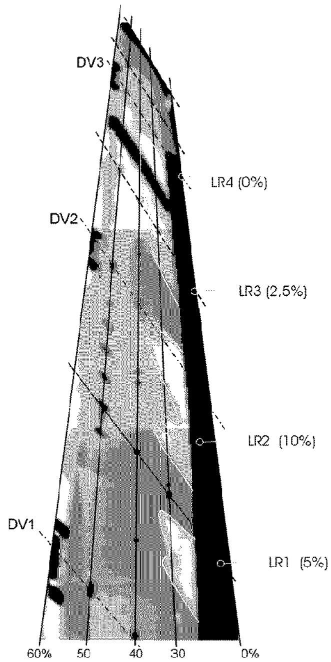

Fig. 21 – Suction imperfection effects on transition locations